 By Bill Travis, Senior Technical Editor

1V, 100A supplies: PLUGGING EFFICIENCY LEAKS

ICs THAT CONSUME 1V, 100A ARE JUST AROUND THE CORNER. MANUFACTURERS OF REGULATOR ICs AND POWER SEMICONDUCTORS ARE BUSY DESIGNING CIRCUITS AND DEVICES THAT FULFILL THAT LOFTY REQUIREMENT.

I CONCEIVED THIS ARTICLE as a "hands-on" project, in which I would attempt to design and build an efficient 1V, 100A dc/dc converter. After conferring with many industry experts, I quickly abandoned that naive ambition. First, it is practically impossible to breadboard such a high-power design using manageable components. I had envisioned merrily soldering wires to power MOSFETs housed in TO-3 or TO-220 packages. Wrong vision: The connection wires alone in these conventional packages would lead to efficiency losses of 20 to 30%. The only hope for any appreciable efficiency hinges on the use of surface-mount devices on a fully laid-out, committed pc board. The second reason to abandon the hands-on design effort was a dose of humility. Power-supply experts, working at regulator-IC and power-semiconductor facilities, are busy preparing 1V, 100A designs. These designs take much expertise and several designer-months to realize. I could, if I were lucky, possibly reinvent the wheel and, more likely, come up with an inferior wheel. So, instead, this report is an update on the efforts of several manufacturers to meet the upcoming 1V, 100A industry requirement, with a perfunctory hands-on look at some reference designs.

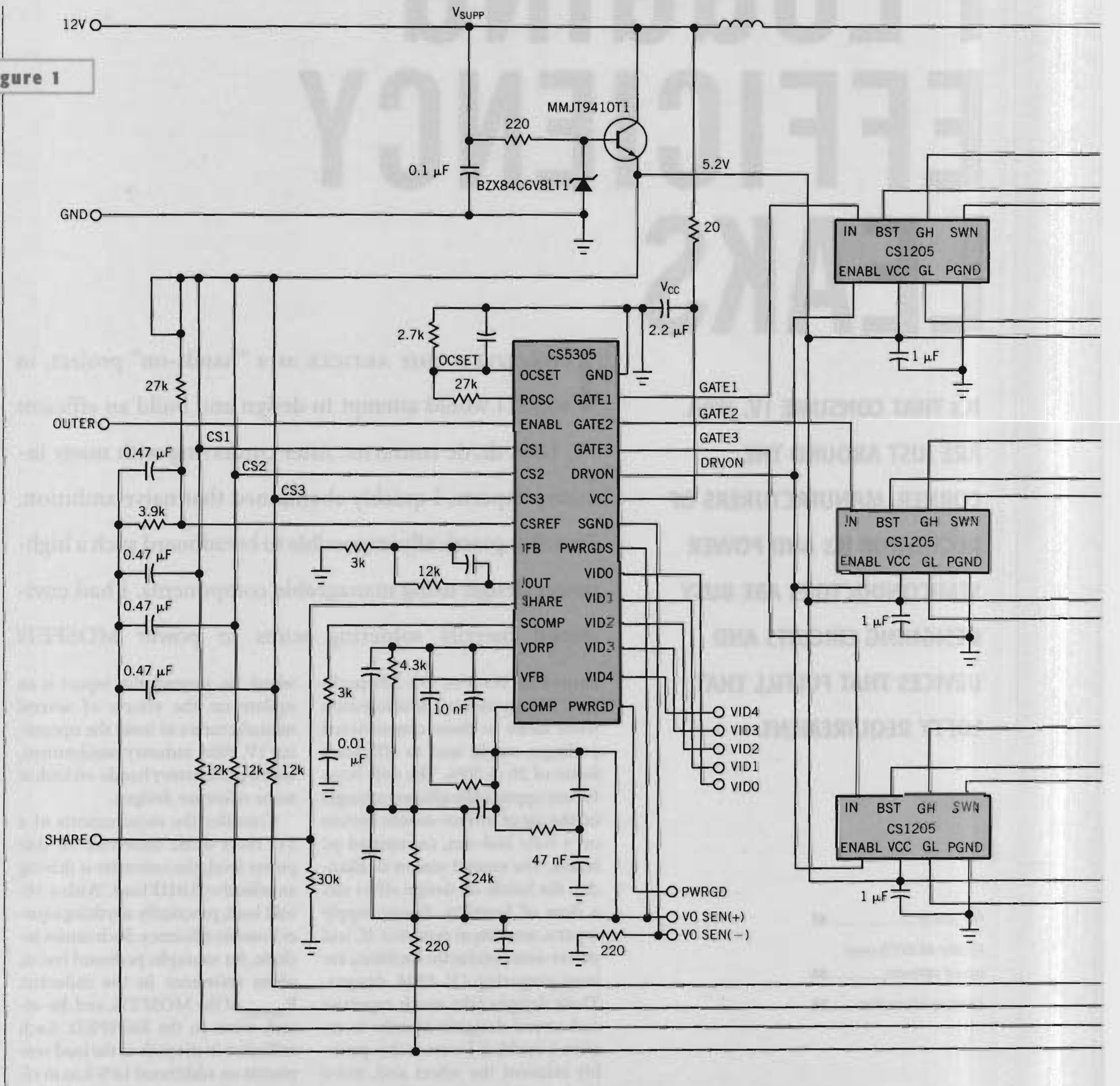
Consider the requirements of a 1V, 100A dc/dc converter. At that power level, the converter is driving an effective 0.01Ω load. With a 10-mΩ load, practically anything causes losses in efficiency. Such causes include, for example, pc-board traces, series resistance in the inductor, $R_{DS(ON)}$ of the MOSFETs, and die-attach wires in the MOSFETs. Each milliohm in the path to the load represents an additional 10% loss in efficiency. Power-MOSFET manufac-

turers are keeping pace with ever-higher load currents by developing devices with lower and lower $R_{DS(ON)}$. One desirable characteristic of power MOSFETs is that you can connect them in parallel, and they share current admirably. Several of the reference designs that follow use parallel-connected MOSFETs. The **sidebar** "Rectifier MOSFETs need special attributes" explains some of the special requirements of MOSFETs used as synchronous rectifiers in buck regulators.

MULTIPHASE DESIGNS DOMINATE

Several manufacturers are concentrating on 12V-input regulators. The Intel VRM (voltage-regulator-module) specs, for example, use 12V input. Most of these suppliers are designing multiphase buck converters. An example is On Semiconductor's demo board (**Figure 1**). A multiphase converter is admittedly more complex than a single-phase design, but it has some important advantages. Because each phase handles only a fraction of the output current, the converter can use smaller power MOSFETs. Moreover, the multiphase structure has the effect of multiplying the converter's switching frequency by the number of phases, so you

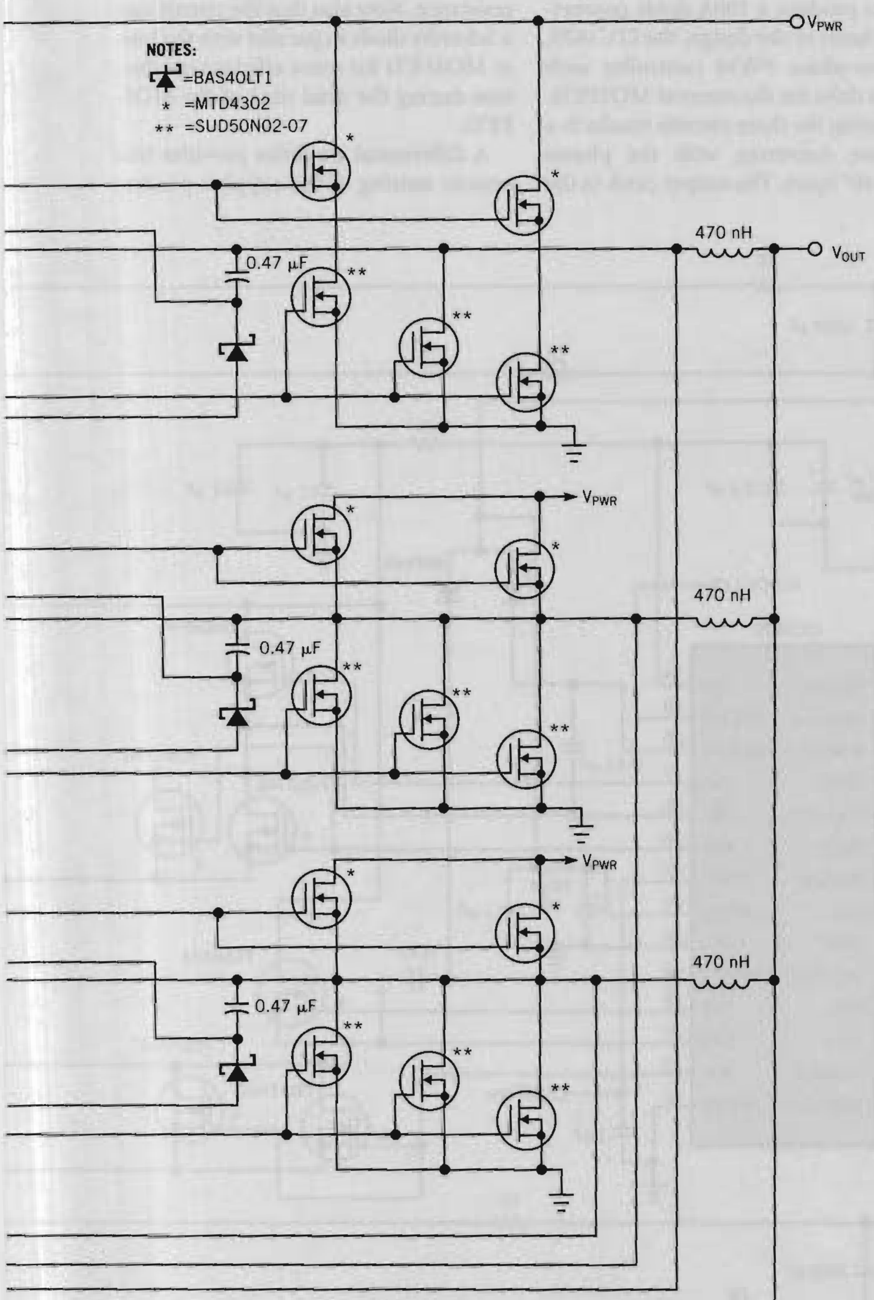
Figure 1



A demonstration board from On Semiconductor can handle 100A output current.

can use smaller inductors and capacitors at the output. Most multiphase buck converters use a switching frequency of approximately 250 kHz. Below this rate, the inductor and capacitor values become unwieldy. Above this frequency, the switching losses of the upper MOSFET become appreciable.

The On Semiconductor design in **Figure 1** uses a CS5305 three-phase VRM controller and three CS1205 MOSFET drivers. For clarity, **Figure 1** doesn't show the large banks of parallel-connected input and output capacitors. The controller IC follows Intel specs in that it accepts a 5-bit VID (voltage-identification) code that determines the output voltage. The standard data sheet for the CS5305 calls for only two MOSFETs per phase. You can see in **Figure 1** that the demo board uses five MOSFETs per phase—two in parallel for the upper devices and three in parallel for the lower devices. On Semiconductor modified the demo boards to produce a 12V-to-1V, 100A converter. The CS5305 features single-wire current sharing, a feature that allows you to connect two of the ICs in parallel with10%-accurate current sharing.



AT A GLANCE

- Requirements for 100A supplies are just around the corner.
- Upper and lower MOSFETs in a buck regulator have different requirements.
- At 100A, the load represents just a few milliohms.
- At 100A, surface-mount devices are the only way to go.

The 5-bit VID codes in the standard CS5305 produce an output of 1.1 to 1.85V at currents as high as 81A. With a code of 11110, the modified circuit produces 1V at currents as high as 100A. The CS5305 measures and adjusts (equalizes) current in each phase. It accomplishes this task by measuring the inductor current in each phase. The 0.047-µF capacitors at the left side of **Figure 1** provide a measure of the inductor current. The voltage across each capacitor is equal to the product of the output current and the inductor's series resistance. Any difference in current in the phases activates an error amplifier that adjusts the PWM signal to the phases. This technique results in essentially lossless current sensing (except for the losses in the inductors' series resistance, which would occur anyway).

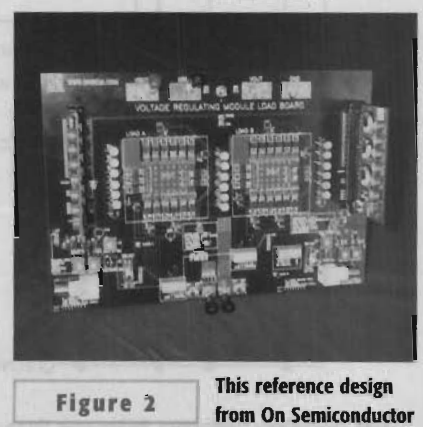


Figure 2 **This reference design from On Semiconductor accepts one or two 100A demo boards.**

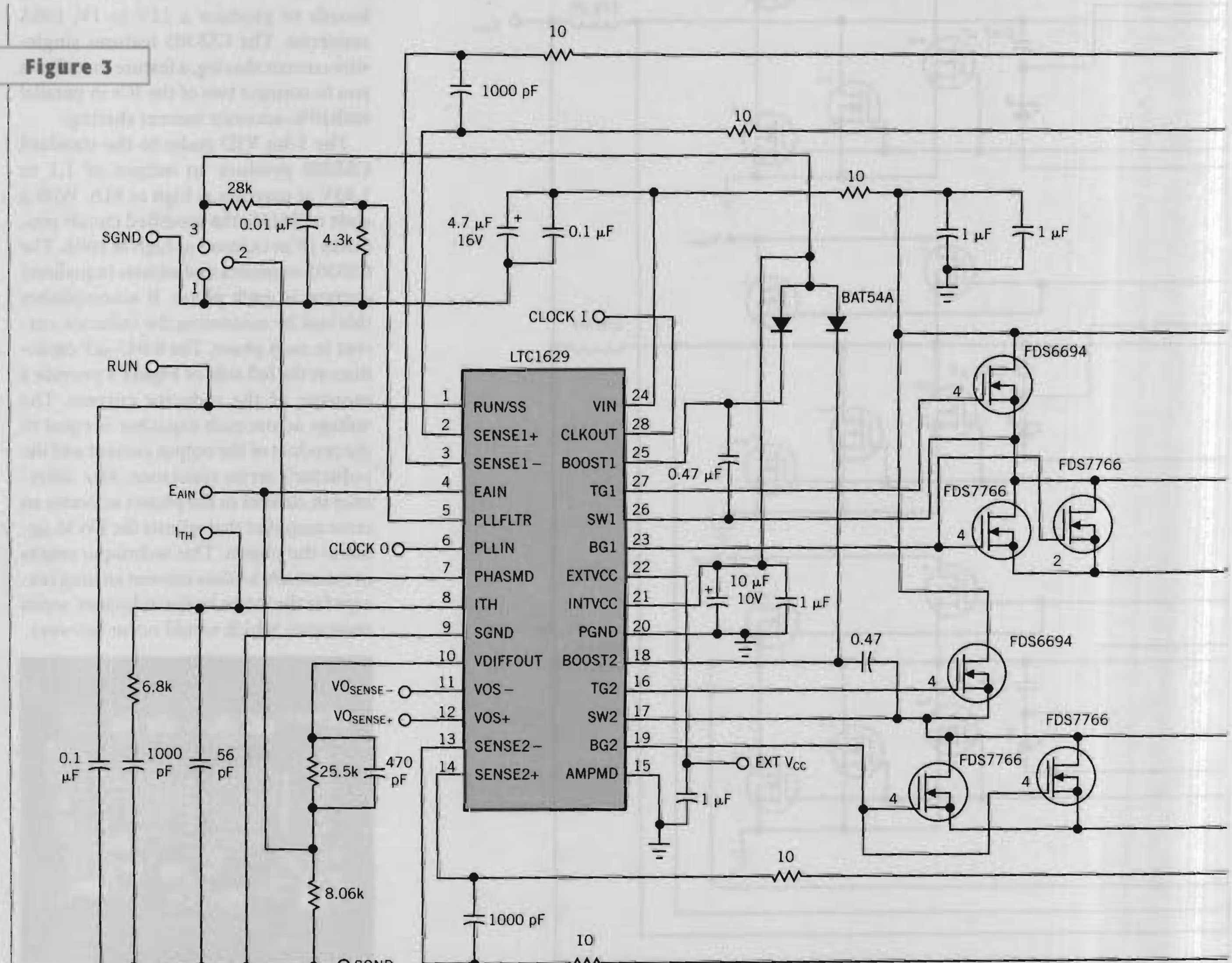
Figure 2 shows an On Semiconductor reference-design "load board" that accommodates one or two CS5305 demo boards. Each demo board is capable of 1V, 100A operation. Plugging a second board in results in 50/50 current sharing. To measure efficiency at 1V, 100A, I constructed a passive load comprising 10 0.1Ω, 10W resistors connected in parallel with heavy copper braid. Measurements showed that the demo board consumed 12.25A at 12V for total input power of 147W. Efficiency is output-power-divided by total input power, or 68%. Note that a loss of efficiency occurs in the socketing of the demo board. Despite multiple contacts and ground returns, contact resistance does exist in the socket. I estimate a loss of 5 or 6% in the connections, and On Semiconductor Application Engineer Jim Friel concurs. The approximate 73% resulting efficiency figure is reasonable, given the large current demand. (Remember, a linear regulator would consume 1100W.)

SIX-PHASE DESIGN EASILY PRODUCES 100A

A reference design from Linear Technology uses three of the circuits in **Figure 3** to produce a 100A dc/dc converter. The heart of the design, the LTC1629, is a two-phase PWM controller with built-in drive for the external MOSFETs. Combining the three circuits results in a six-phase converter, with the phases spaced 60° apart. The output clock in the LTC1629 provides the phase spacing and allows you to connect as many of six of the circuits together, for as many as 12 phases. With 12 phases, you could configure a converter that handles currents as high as 200A. Note that the circuit in **Figure 3** uses one MOSFETs in for the upper switch and two MOSFETs in parallel for the lower switch. The MOSFETs have multiple package connections to the drain and the source to minimize series resistance. Note also that the circuit uses a Schottky diode in parallel with the lower MOSFETs for more efficient conduction during the dead time of the MOSFETs.

A differential amplifier provides true remote sensing of the supply's positive

Figure 3



Linear Technology's reference design uses three of these circuits to make six phases.

and negative output terminals. This Kelvin-type sensing is absolutely necessary in applications requiring high current, such as 100A. Note that, in **Figure 3**, the LTC1629 effects current sensing by measuring the drop across a 0.003Ω resistor in series with each output. Assuming the 100A average current divides equally among the six phases, each 0.003Ω resistor dissipates 0.833W, for a total of 5W, or a 5% loss in efficiency. The IC uses the current sensing to initiate current foldback during short-circuit conditions. The circuit provides gate drive for the upper MOSFETs by using a charge-pump technique. External bootstrap capacitors connected to the boost terminals of the LTC1629 charge through diodes and then place their charge voltage across the gate-source terminals of the top-side MOSFETs. **Figure 4** shows the six-phase reference design. Measurements showed total efficiency of 73% at 1V, 100A output. Load regulation for the circuit was excellent; the 1.009V output dropped by only 6 mV when the load increased from 2 to 100A. Line regulation was also good; the output varied by ±3 mV with input supplies ranging from 10.8 to 13.2V.

Figure 4 This reference circuit uses six phases to supply 1V, 100A.

POWER PACKAGE UPS EFFICIENCY

International Rectifier's recently introduced power circuits, dubbed iPOWIRs, contain layout-critical components that form a building block from which you can construct multiphase buck regulators. **Figure 5** shows a typical configuration. Originally restricted to 15A continuous current, the iP2001 now can handle 20A continuous current. Each iP2001 contains a 1-μF decoupling capacitor, a MOSFET driver with dead-time control, an upper and lower synchronous-rectifier MOSFET, a Schottky diode, and a 2.2-μF capacitor across the input supply. **Figure 5** shows a four-phase converter. At 20A per phase, this circuit can handle 80A output. A 100A converter would entail the use of five or six phases.

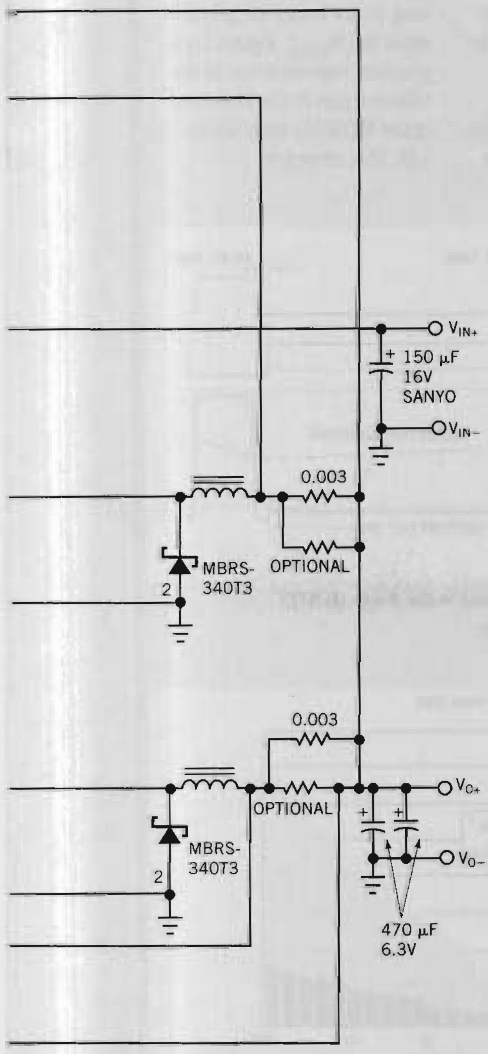
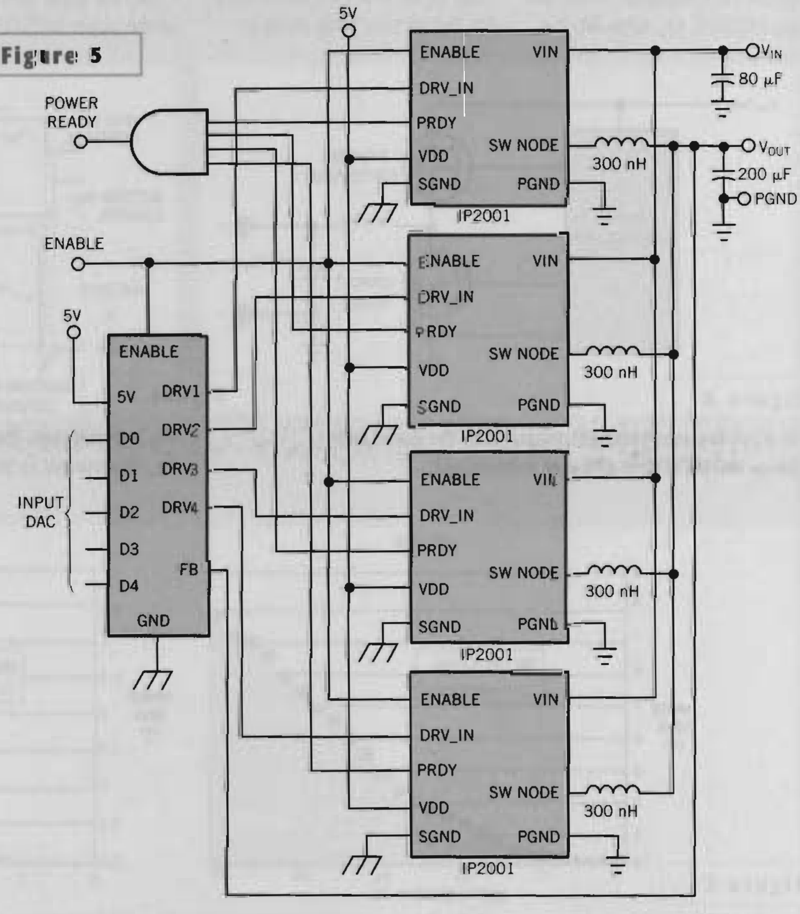


Figure 5



Power modules from International Rectifier considerably boost conversion efficiency.

International Rectifier has conducted tests that indicate the iP2001 can increase efficiency in systems by a significant percentage. For example, a comparison of conversion efficiency against an equivalent DPak configuration showed roughly equivalent efficiency to approximately 20A (85% at 20A). Beyond 20 to 25A, the efficiency of the DPak configuration drops rapidly. At 60A, the efficiency of the DPak circuit falls to approximately 78%, and the iP2001 circuit still delivers approximately 84%, a difference of 6%. The differences stem largely from layout problems associated with discrete components. Stray inductances and connection resistances can result in significant losses in efficiency.

RECTIFIER MOSFETs NEED SPECIAL ATTRIBUTES

To obtain decent efficiency figures from a high-current buck regulator, you need to use power MOSFETs as synchronous rectifiers. At output currents in the high tens of amperes, the forward-drop power losses of Schottky-diode rectifiers are prohibitive. For optimum efficiency, the upper and lower MOSFETs in a synchronous-rectifier arrangement (**Figure A**) need different attributes. **Figure B** shows the gate-control signals, the FETs' voltage waveforms, and the inductor current in a typical buck regulator. When the top MOSFET, Q_1, turns on, the output inductor conducts current according to the circuit's L/R time constant, with R equal to the sum of the load, power-MOSFET, and supply resistances. When the bottom MOSFET, Q_2 turns on, the inductor takes its current from that transistor. Note that Q_2 conducts current in the reverse direction—from source to drain. The PWM controller must provide dead time, a period when both MOSFETs are off, to prevent cross-conduction, or "shoot-through." During the dead time, the inductor must take its current from someplace, so the intrinsic body diode in the lower MOSFET conducts. Some designs increase efficiency by using a Schottky diode in parallel with the lower MOSFET.

In a buck regulator with a relatively low duty cycle, switching losses dominate the upper MOSFET's power-loss budget. The duty cycle of a buck regulator is roughly equal to the voltage-transformation ratio. For example, a 12V-to-1V converter has a duty cycle of approximately 8%. For the upper MOSFET, conduction losses decrease in importance with decreasing duty cycle. The drain-source voltage of the upper MOSFET swings rail-to-rail (in the cited example, 12V p-p). Because of this large swing and the fact that the upper MOSFET has a low duty cycle, the finite rise and fall times of the voltage waveform produce significant switching losses in this transistor. In contrast, the lower MOSFET has little voltage swing ($I_LR_{DS(ON)}$), and its conduction time is relatively long, so the losses are primarily equal to $I_L^2R_{DS(ON)}$. **Figure C** is a graphical representation of the relative losses in the lower and upper MOSFETs for a 12V-to-1.2V, 25A converter.

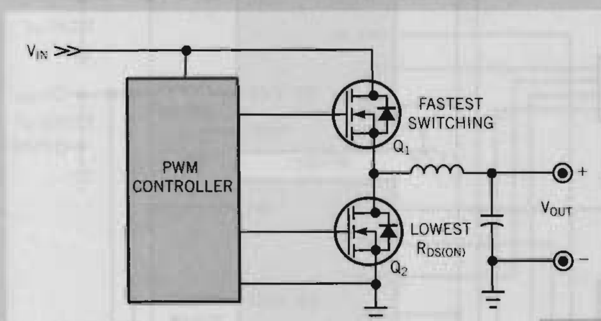


Figure A

In a synchronous-rectifier configuration, the upper and lower MOSFETs have different requirements.

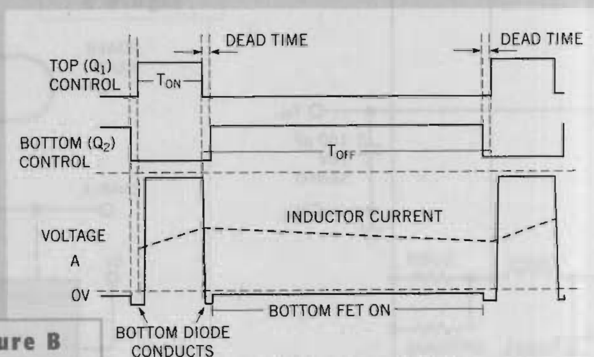


Figure B

During dead time, the body diode in the lower MOSFET supplies current to the inductor.

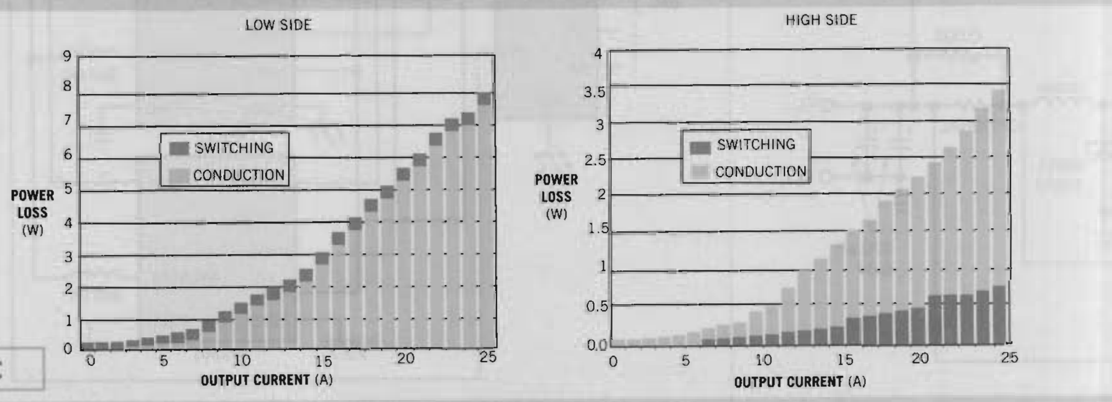


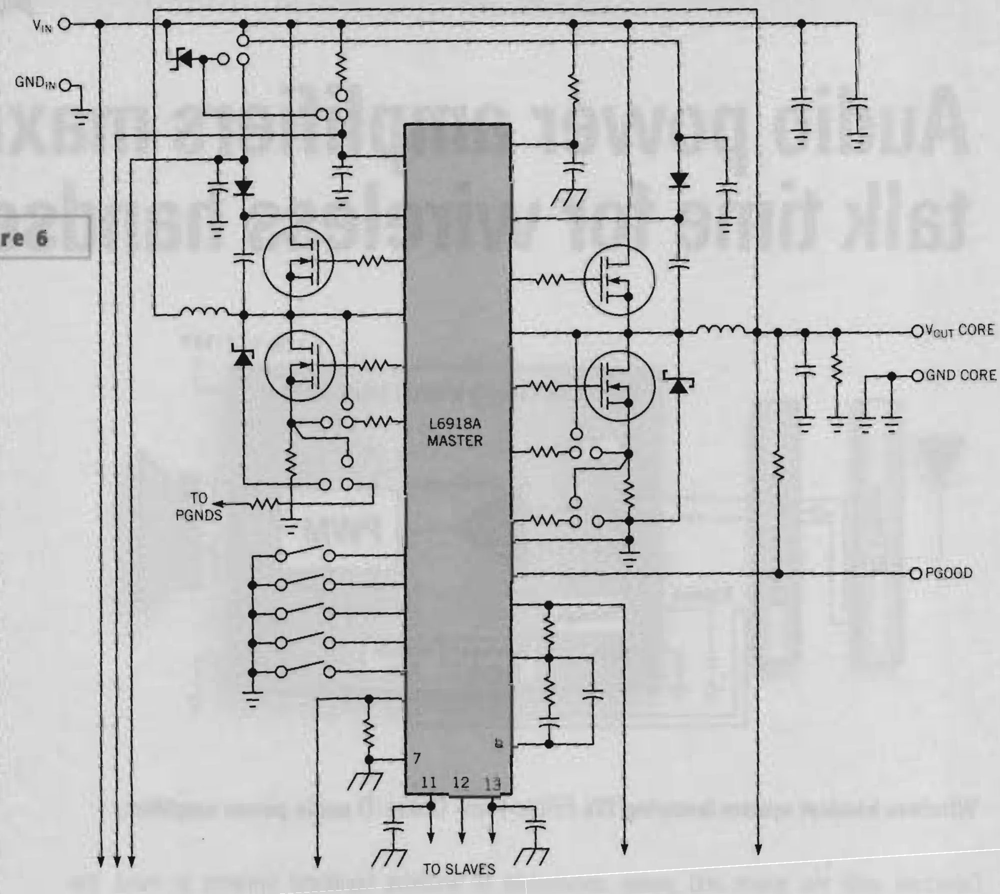
Figure C

The upper and lower MOSFETs in a buck converter display different flavors of losses.

STMicroelectronics offers a two-phase master/slave multiphase controller that you can expand to obtain four, six, or eight phases. **Figure 6** shows the two-phase L6918A master; you can easily obtain 100A output current by adding two or three L6918 slaves (four or six additional phases). The L6918 ICs contain charge-pump circuitry for driving the gates of the upper MOSFETs. The circuits use a 5-bit VID code according to the Intel VRM 9.0 spec, to select an output voltage of 1.1 to 1.85V in 25-mV steps. The L6918 operates at switching frequencies to 1 MHz. It provides overcurrent protection by using either a sense resistor or by sensing the lower MOSFET's $R_{DS(ON)}$.

IC and discrete-device manufacturers are gearing up for the extremely heavy currents that the latest generation of VLSI circuits will demand. Some suppliers are concentrating on a 12V bus voltage with multiphase converters. In addition to those companies already mentioned, Analog Devices, Intersil, National Semiconductor, and Texas Instruments supply multiphase buck-regulator ICs. Bill Andreycak of Texas Instruments' Unitrode division plans on taking another tack. He's setting his sights on a single-phase configuration, using a 48V bus voltage. In the meantime, however, his division of Texas Instruments supplies circuits for another TI division's (Power Trends) 60A multiphase converter.□

Figure 6



You can expand this master/slave arrangement from STMicroelectronics to eight phases.

FOR MORE INFORMATION...

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